Spin Distributions in the Pre-Equilibrium Process

T. Kawano, M.B. Chadwick
T-16, Los Alamos National Laboratory
Los Alamos, New Mexico 87545, USA

Los Alamos

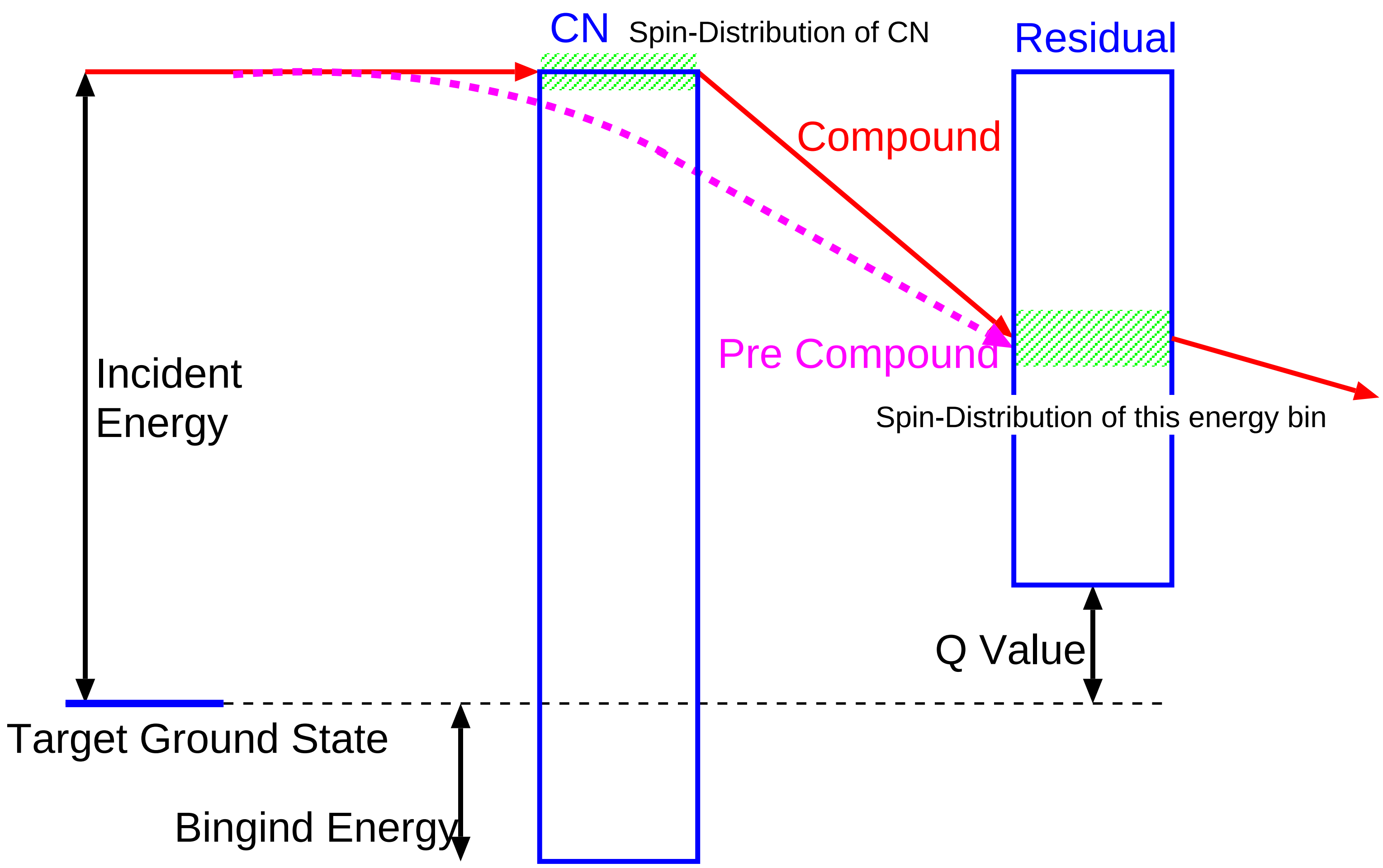
Compound Nuclear Reaction

- Spin Distribution of Compound Nucleus
  - $n + A \rightarrow (A+1)^*$
  - Spin distribution of $(A+1)^*$ is calculated with the optical model transmission coefficients, T_j.

$$R(J) \qquad |I - j| \le J \le I + j$$

- Spin Distribution of the Residual Compound Nucleus (Decay of CN)
  - $(A+1)^* \rightarrow n' + A^*$
  - Spin distribution of A^* is calculated from:
    - the first compound nucleus, $R(J)$,
    - transmission of emitted particle, $T'(j)$, and
    - spin distribution of residual nucleus (continuum), $R'(E_x, J)$.

Compound or Pre-compound Process



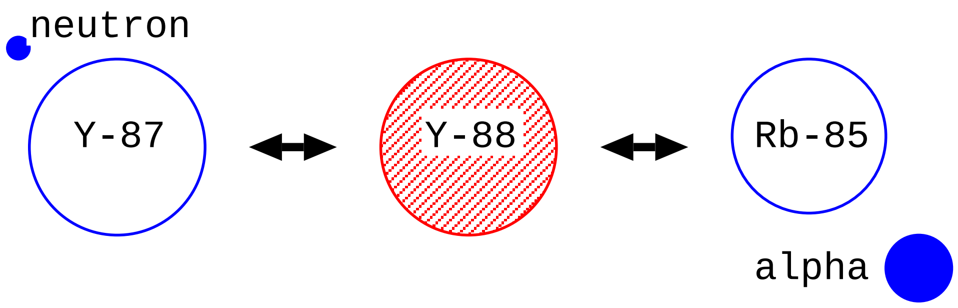
Statistical Theory

Compound Formation Cross Section

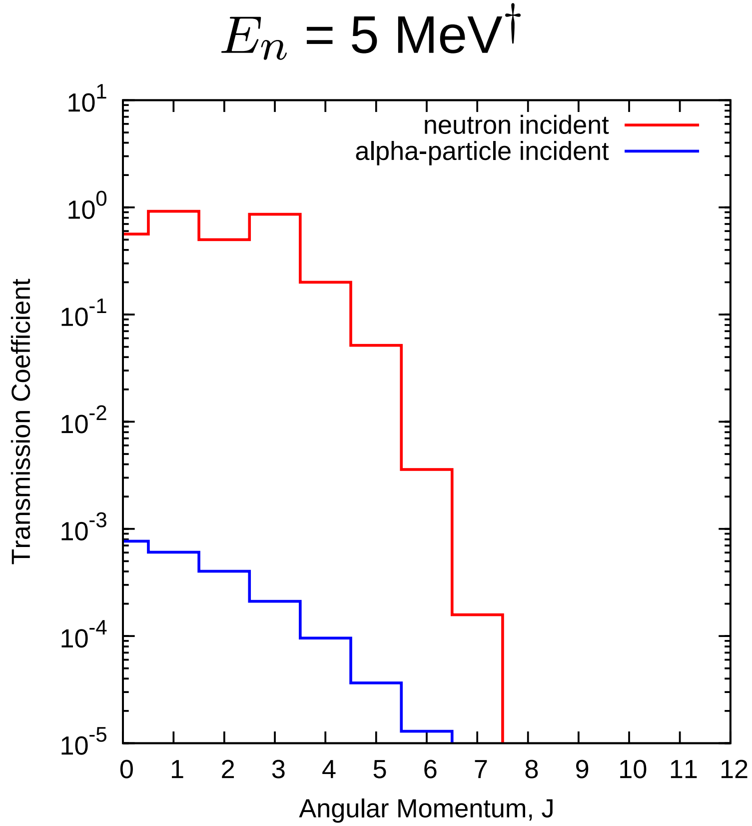
- Decay of CN is independent of the formation of CN,
- however spin distribution of initial CN population depends on the transmission of incident particle.

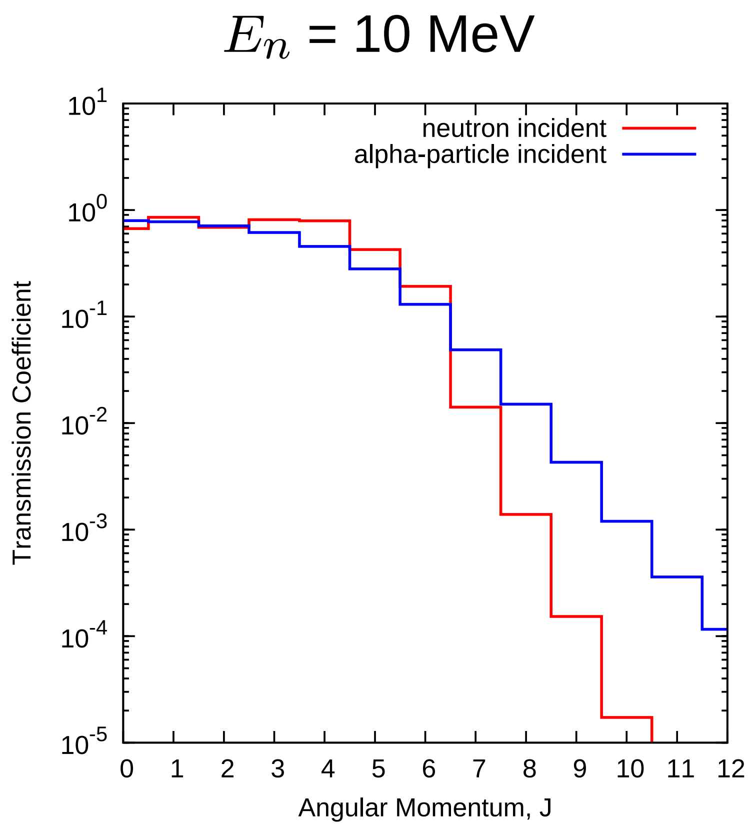
Surrogate Reaction (example)

- For the neutron incident reactions on ^{87}Y, the compound state is ^{88}Y.
- The same compound can be formed by α-particle incident reactions on ^{85}Rb.



Transmission (Optical Model Calc.)





† Equivalent neutron energy,

$$E_n^{CMS} = E_\alpha^{CMS} - Q$$

Pre-Equilibrium Theories (I)

Classical Theory

- Exciton Model
  - Nuclear state — n-particle $(n-1)$-hole state
  - Transition rate — $\lambda_{nn'} = \frac{2\pi}{\hbar^2}|M|^2\rho_{n'}$
  - Solve a master equation — time-dependent occupation probability $P(n,t)$ of the n-exciton states.
  - The matrix element $|M|^2$ is regarded as an adjustable parameter.
  - Generally the exciton model gives a good fit to the energy distribution of emitted particles, however, a traditional exciton model cannot calculate angular distribution.
- Intra-Nuclear Cascade (INC)
  - Cannot apply to low-energy reactions.

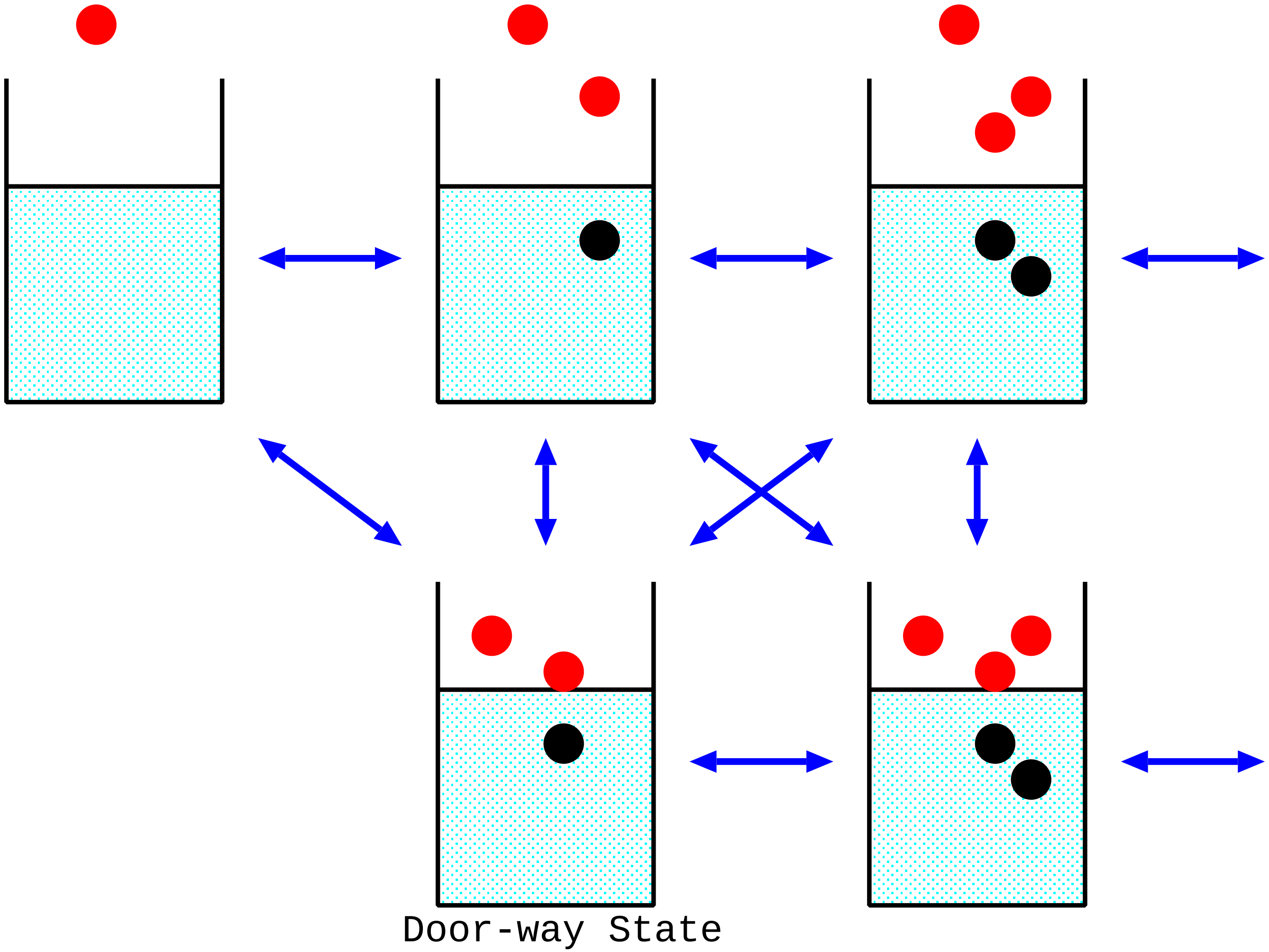
Los Alamos

Pre-Equilibrium Theories (II)

Quantum Mechanical Theory

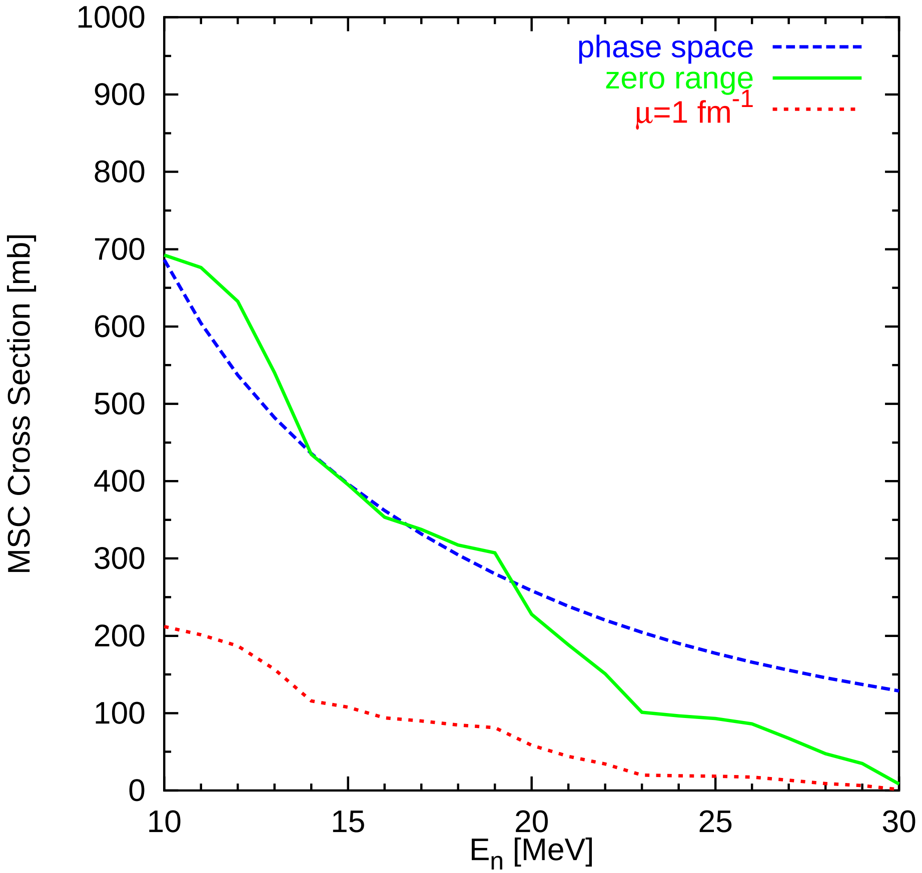
- Feshbach, Kerman, and Koonin (1980) — FKK
- An extension of DWBA to the continuum state
- Particle-Hole excitation — similar to the exciton model
- $\mathcal{Q}$-space (Multistep Compound, MSC)
  - Final state is bound
  - Residual System: $2p$-$1h$, $3p$-$2h$, $4p$-$3h$, $\ldots$
  - MSC gives an isotropic angular distribution
- $\mathcal{P}$-space (Multistep Direct, MSD)
  - At least one particle is unbound
  - Residual System: $1p$-$1h$, $2p$-$2h$, $3p$-$3h$, $\ldots$
  - MSD has a forward-peaked angular distribution

$\mathcal{P}$-Space, $\mathcal{Q}$-Space



Multistep Compound Process (MSC)

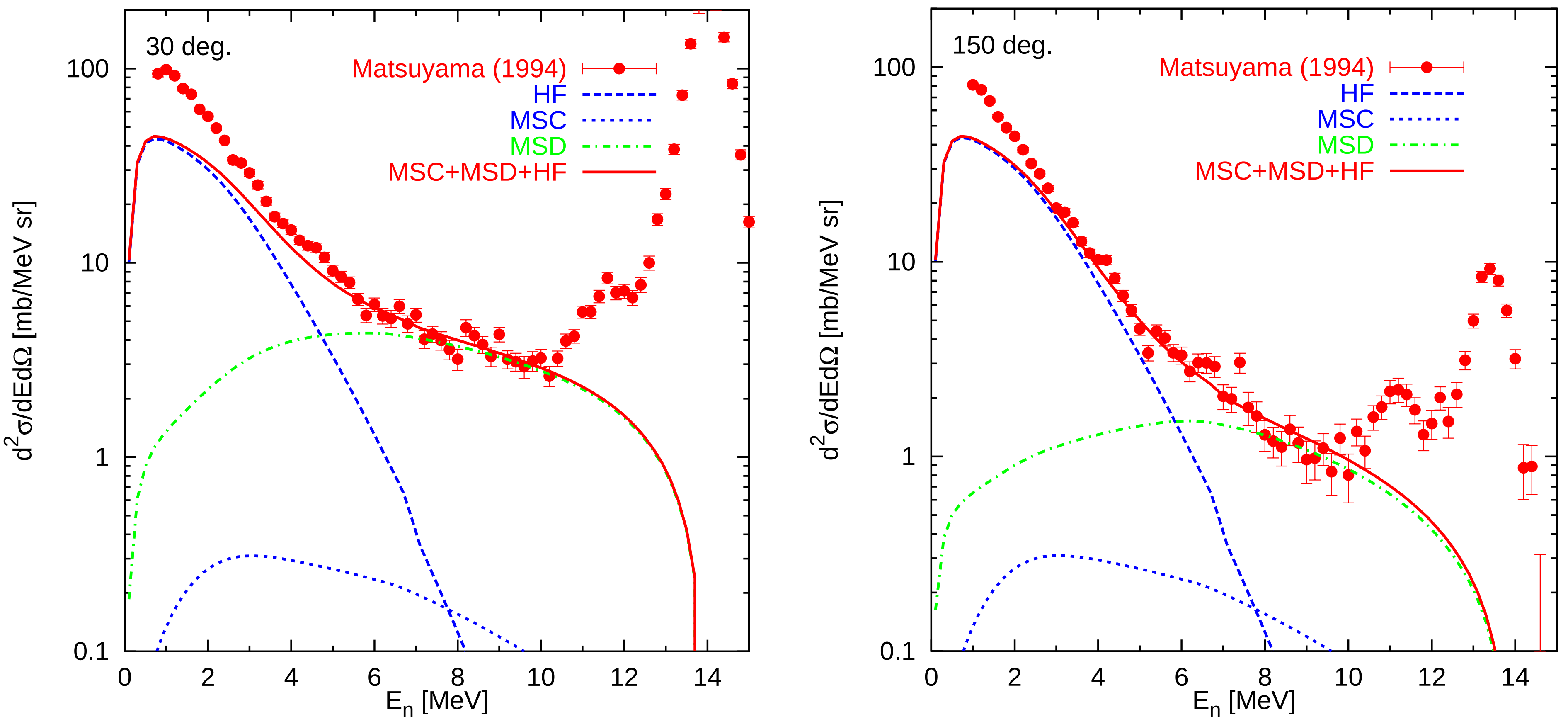
Strength of $2p$-$1h$ Formation



- ^{93}Nb$+n$ reactions.
- Microscopic calculation of doorway state formation cross section.
  - DWBA transition matrix element $\times$ final state density.
  - $\langle p'(ph^{-1})|\mathcal{V}|0\chi_a\rangle\rho_{2p1h}$
- Phase-space approximation of Chadwick and Young.
  - Estimated a fraction of MSC by using a final state density.

Strength of MSC

DDX Data of ^{93}Nb at 14 MeV



Los Alamos

MSD Theories

- FKK: Feshbach, Kerman, Koonin (1980)
  - On-Shell Approximation for Green's Function
- TUL: Tamura, Udagawa, Lenske (1982)
  - Random Phase Approximation (RPA)
  - Adiabatic Approximation for the Second Step
- NWY: Nishioka, Weidenmüller, Yoshida (1988)
  - Random Matrix Theory (GOE)
  - Sudden Approximation for the Second Step
- SCDW: Luo, Kawai, Weidenmüller (1991,1992)
  - Eikonal Approximation for the Second Step

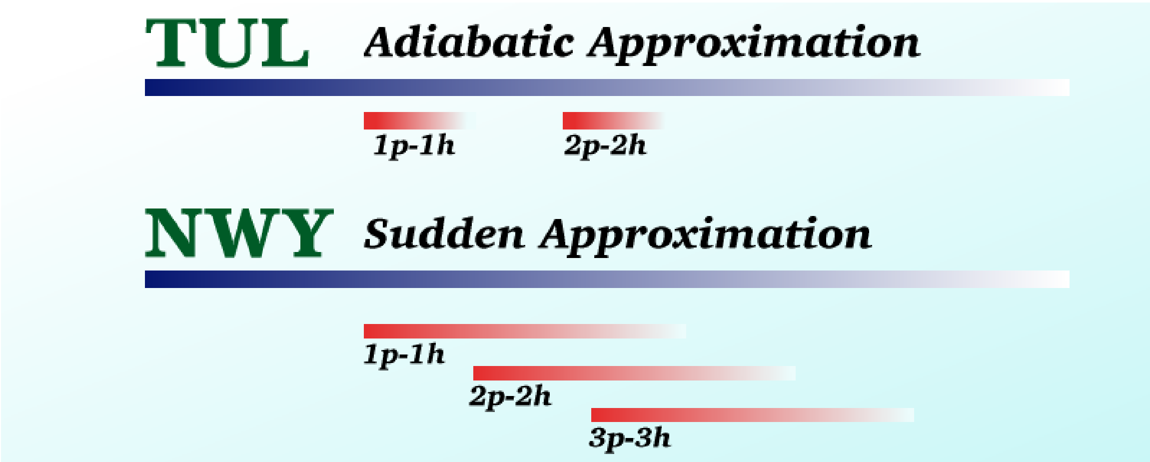
One-step process is dominant below 20 MeV, and the one-step expression of FKK, TUL, and NWY is the same (in principle).

Los Alamos

Comparison of FKK, TUL, and NWY

	FKK	TUL	NWY
Approximation	on-shell	Adiabatic	Sudden
Statistical Average	Each	Each	Final
State density	$\rho_{1p1h} \otimes \rho_{1p1h}$	$\rho_{1p1h} \otimes \rho_{1p1h}$	ρ_{2p2h}
Model	Equidistant	RPA	GOE
Interference	No	No	Yes

Time Scale



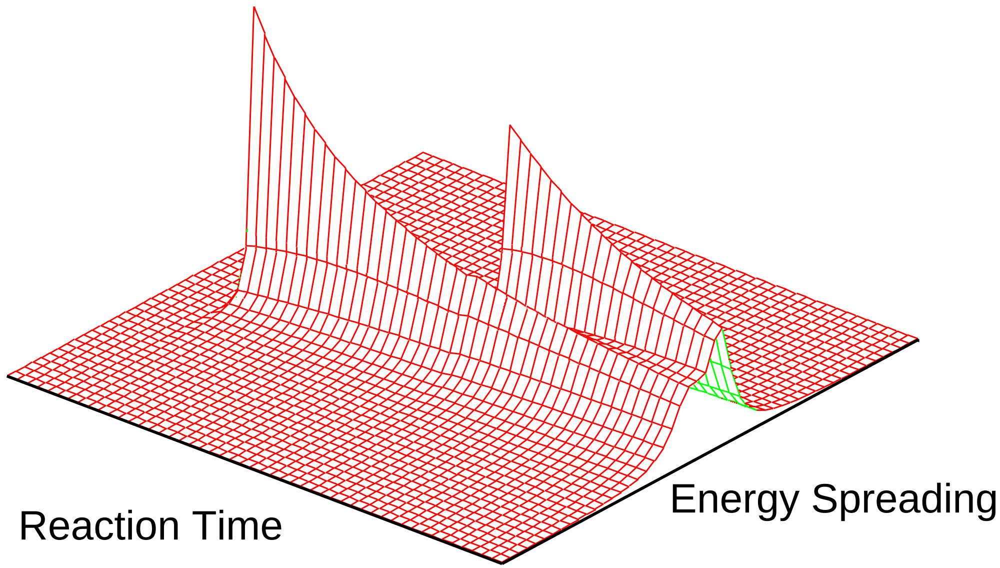
Los Alamos

NWY Theory

- Quantum Mechanical Theory for the Pre-Equilibrium Process (MSD)
- Residual System Statistics
- use so-called True Level Density, $\rho_{\mu m}(E)$ which includes a Residual Interaction, V
- The Level (State) Density is different from the equidistant-spacing model of Ericson and Williams.
- one-step: (DWBA) $\times$ (1p-1h Strength)
- two-step: (2nd order DWBA) $\times$ (2p-2h Strength)
- Sudden Approximation is made for the second step.

Sudden Approximation

- An additional p-h pair creation is much faster than residual configuration mixing.
- An intermediate state is always an $1p$-$1h$ state.
- Amplitudes for the different paths to reach the same final state interfere each other.



Residual System Statistics

- Observable Cross Sections
  - various microscopic 2p-2h state excitation averaged over the residual state
- True Level Density of Sato, Takahashi, and Yoshida
  Based on the Random Matrix Model
  Z. Phys. A, **339**, 129 (1991).
- Hamiltonian for the Nuclear System $H = h + V$
  - h independent particle model

$$(h - \epsilon_{m\mu})|m\mu\rangle = 0$$

  - V residual interaction: V is assumed to form a GOE which is characterized by a second moment $\mathcal{M}_{mn}$

True Level Density

Unperturbed State Density

$$\rho_m^{(0)J\pi}(E) = \sum_\mu \delta(E - \epsilon_{m\mu})$$

Exciton State Density for fixed $J\pi$

$$\rho_m^{J\pi}(E) = -\sum_\mu \frac{1}{\pi}\mathrm{Im}\frac{1}{E - \epsilon_{m\mu} - \sigma_m^{J\pi}(E)}$$

Saddle Point Equation

$$\sigma_m^{J\pi}(E) = \sum_n \mathcal{M}_{mn} \int \rho_n^{(0)J\pi}(\epsilon)\frac{1}{E - \epsilon - \sigma_n^{J\pi}(E)}d\epsilon$$

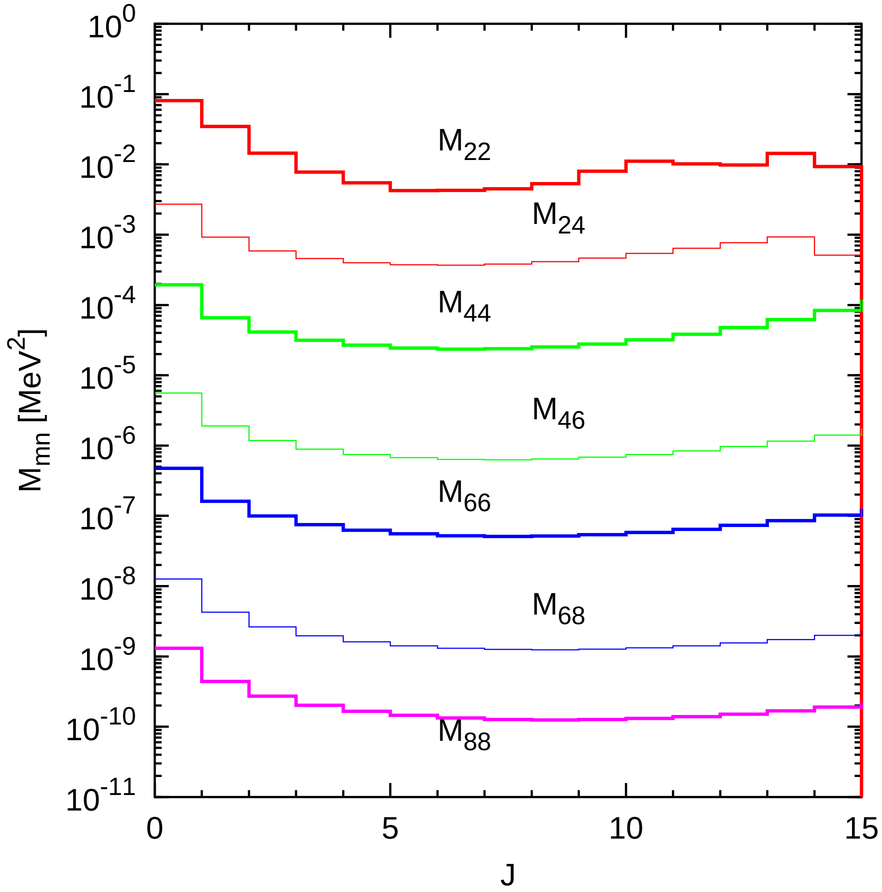
Los Alamos

Second Moment

Calculated for ^{208}Pb, with the M3Y-Paris Interaction which contains the central part V^C and the tensor part V^T

$$V^C = \sum V_{st}^C (\sigma_1 \cdot \sigma_2)(\tau_1 \cdot \tau_2) Y(\mu r)$$

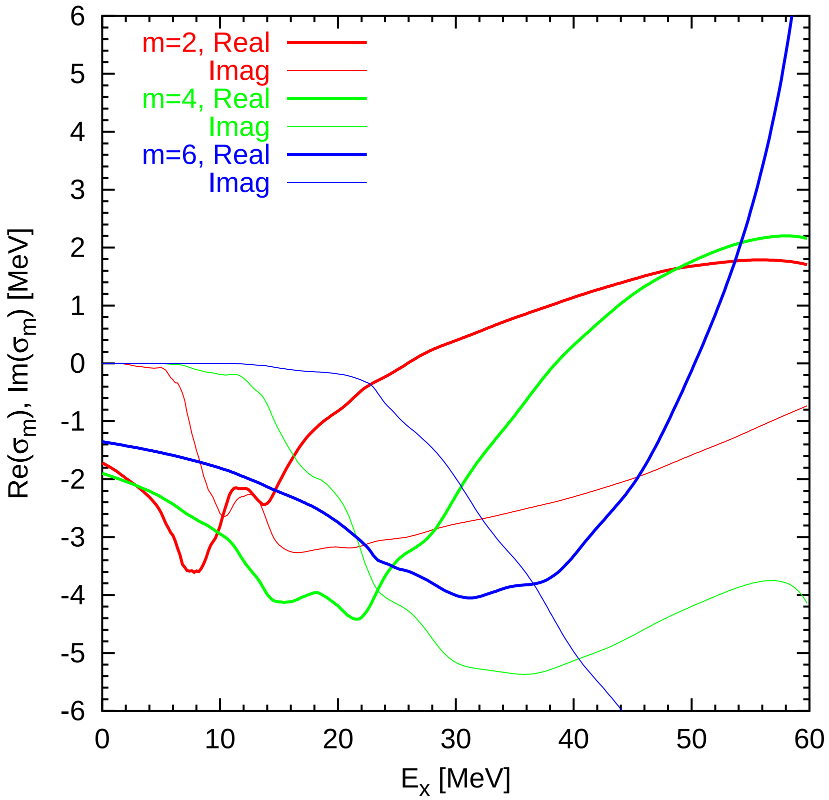
$$V^T = \sum V_t^T (\tau_1 \cdot \tau_2) S_{ij} Y(\mu r)$$



Saddle Point Value

true level density

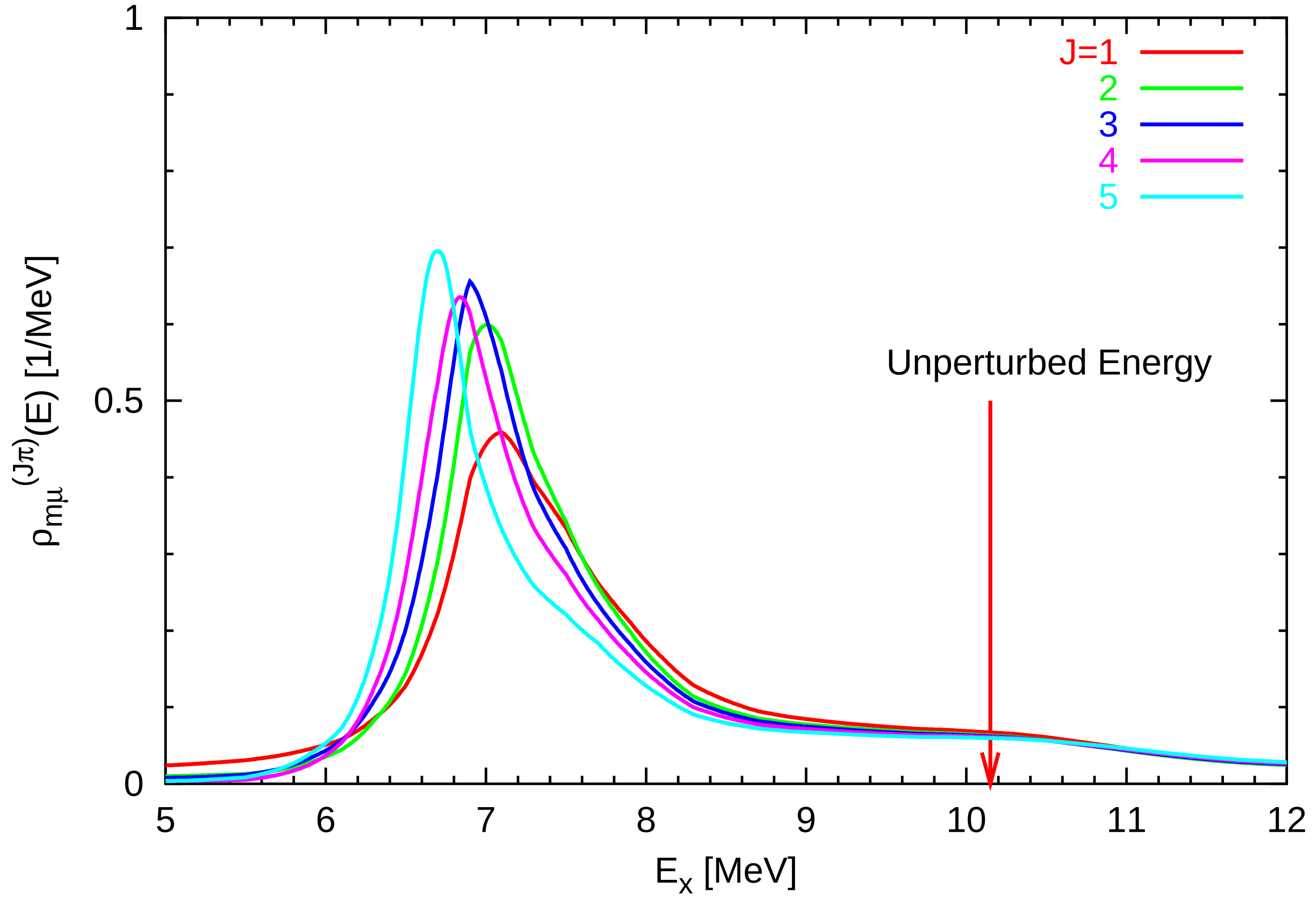
$$\rho_m^{I_B}(E_x) = -\frac{1}{\pi}\mathrm{Im}\frac{1}{E_x - \epsilon_B - \sigma_m^{I_B}(E_x)}$$



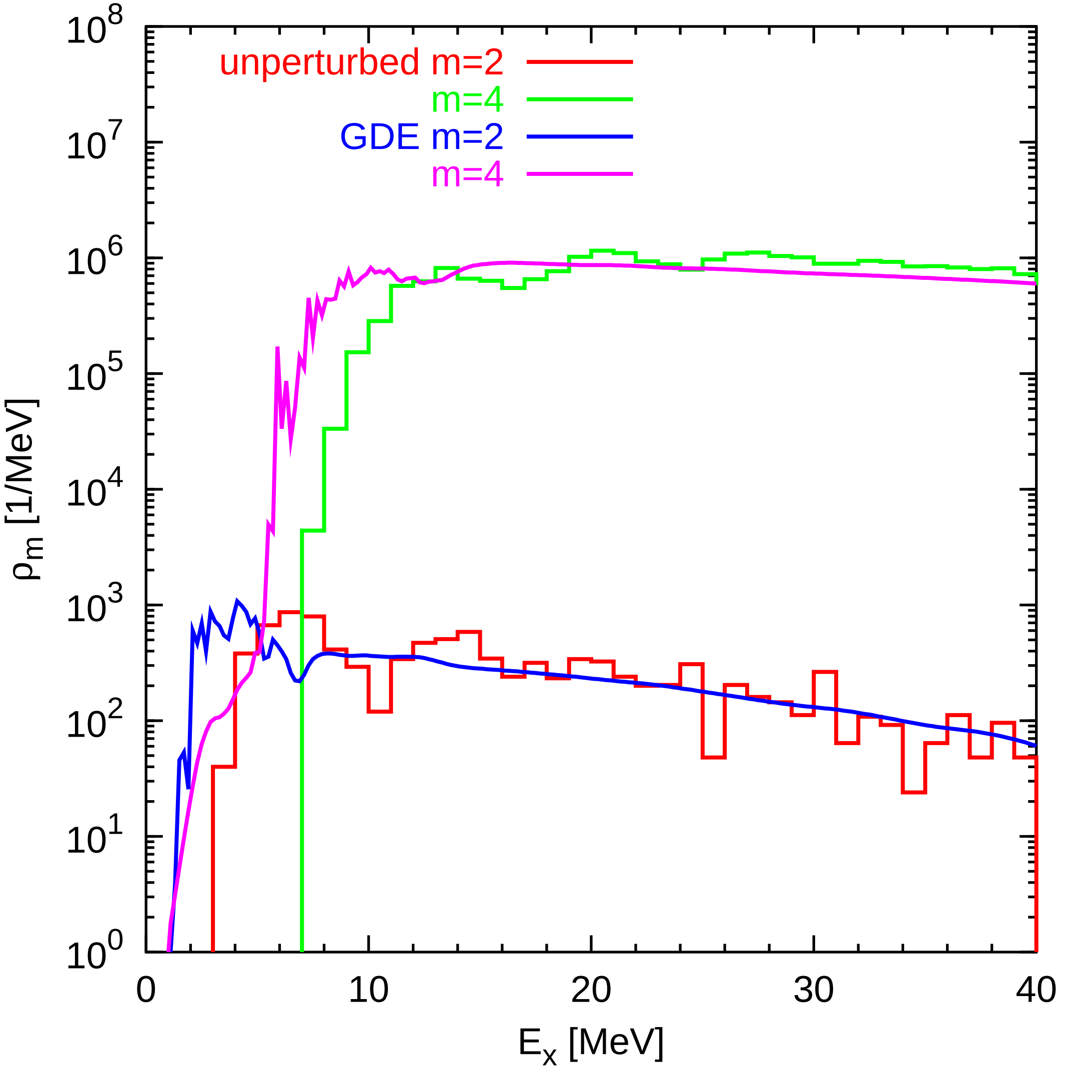
- $\mathrm{Re}(\sigma_m)$ = energy shift
- $\mathrm{Im}(\sigma_m)$ = energy spread

Example: 1p-1h State Distribution

^{208}Pb, $|1g_{7/2}(0h_{9/2})^{-1}\rangle_\nu$, E_x =10.15 MeV



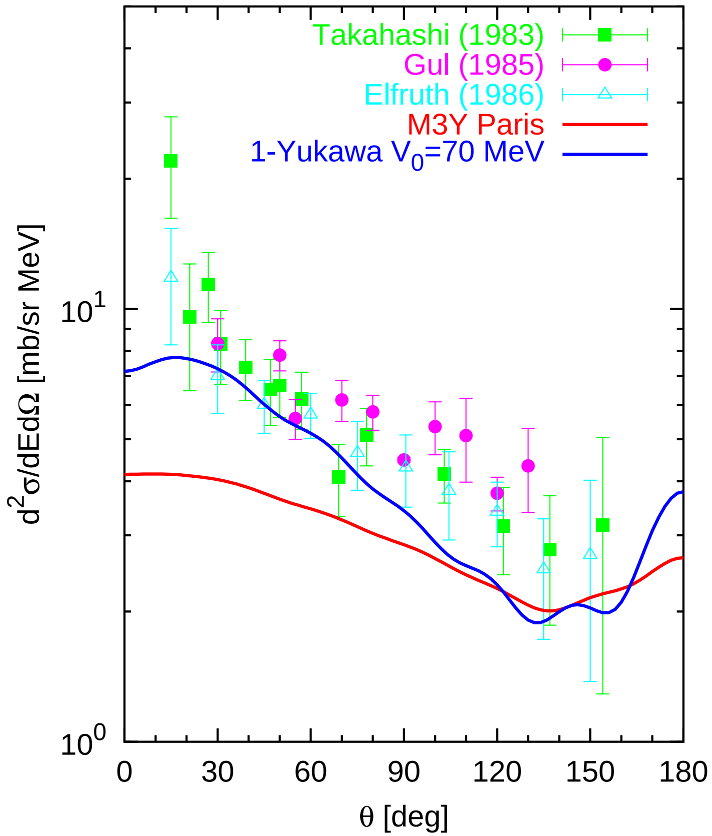
p-h State Density



One-Step Cross Section

$$\frac{d^2\sigma_{ba}}{dEd\Omega} = \frac{(2\pi)^4}{k_a^2} \sum_{\mu} |\langle \chi_b^{(-)} u_{m\mu} | \mathcal{V} | \chi_a^{(+)} u_0 \rangle|^2 \rho_{m\mu}(E_x)$$

- ^{208}Pb(n,n') reaction at:
  $E_{in} = 14.5$,
  $E_{out} = 7.5$ MeV
- Walter-Guss' optical potential
- M3Y interaction
- Yukawa interaction:
  $V_0 = 70$ MeV, and $r_0 = 1$ fm



Los Alamos

Bonetti Approach

FKK One-step Calculation

$$
\begin{aligned}
\frac{d^2\sigma_{ba}}{dEd\Omega} &= \frac{(2\pi)^4}{k_a^2}\sum_\mu |\langle \chi_b^{(-)} u_{m\mu}|\mathcal{V}|\chi_a^{(+)} u_0\rangle|^2 \rho_{m\mu}(E_x) \\
&= \sum_j \frac{(2\pi)^4}{k_a^2}\overline{|\langle \chi_b^{(-)} u_{m\mu}|\mathcal{V}|\chi_a^{(+)} u_0\rangle|^2}(2j+1)\hat{\rho}_{1p1h}(E_x,j) \\
&= \sum_j \left\langle \left(\frac{d\sigma_{ba}}{d\Omega}\right)_{DWBA}\right\rangle_j \hat{\rho}_{1p1h}(E_x,j)
\end{aligned}
$$

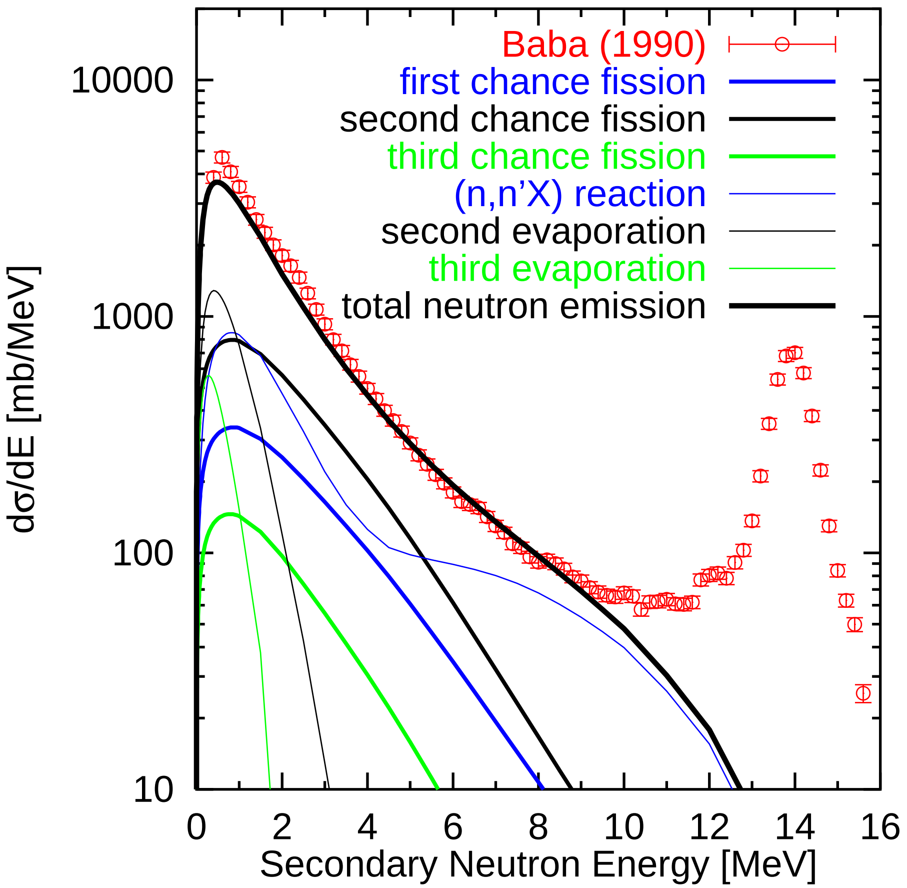
- Averaged DWBA cross section
  - particle-hole excitation, with angular momentum transfer of j
- Phenomenological level density $\hat{\rho}_{1p1h}(E_x,j)$

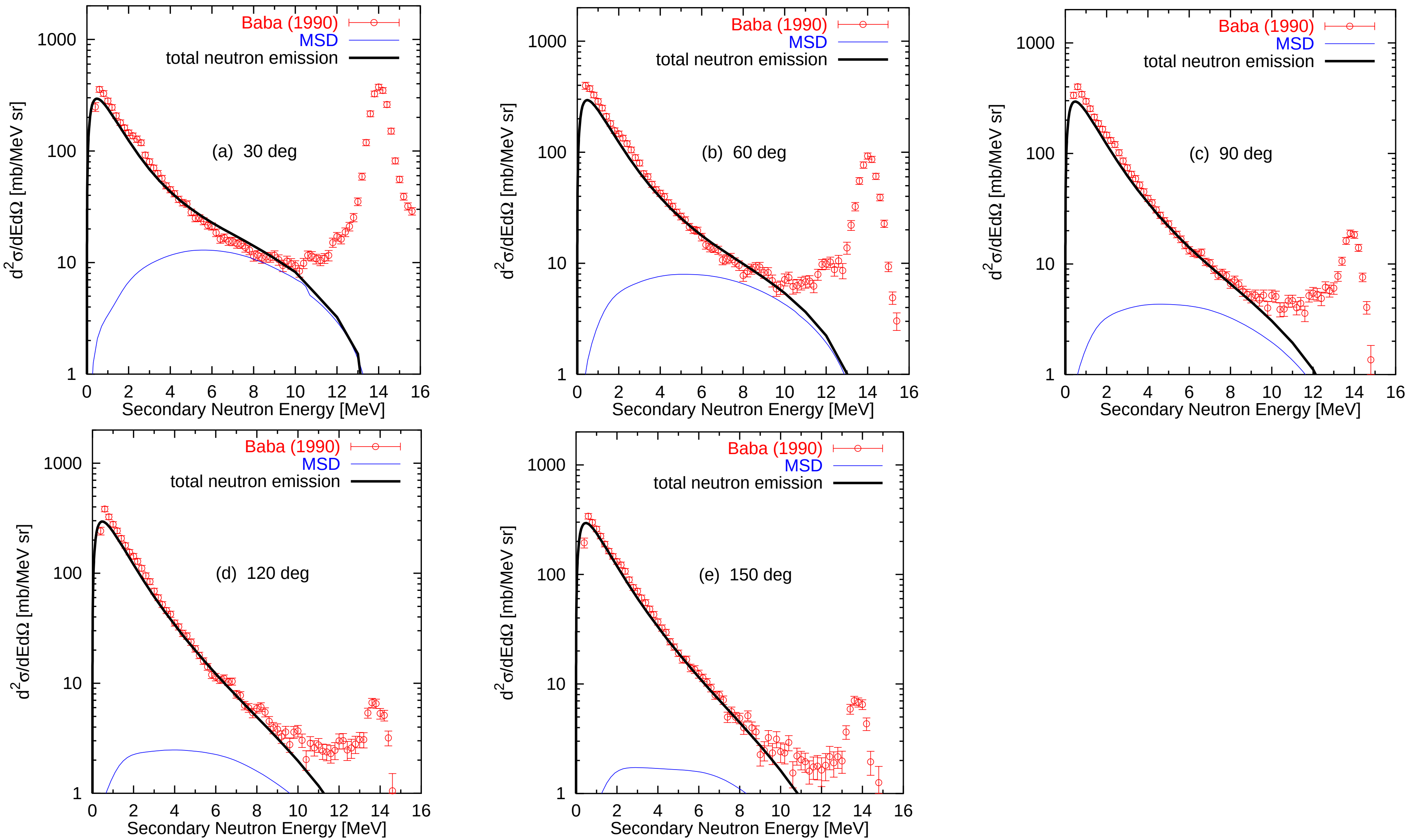
Example — U-238

Neutron Inelastic Scattering

^{238}U(n,xn), $E_n = 14.1$ MeV

- DWBA formfactor for p-h excitation is a simple Yukawa-form.
- The strength of Yukawa interaction V_0 is adjusted to experimental DDX data.
- $V_0 = 50.5$ MeV
- Multi-Step Compound (MSC) included.

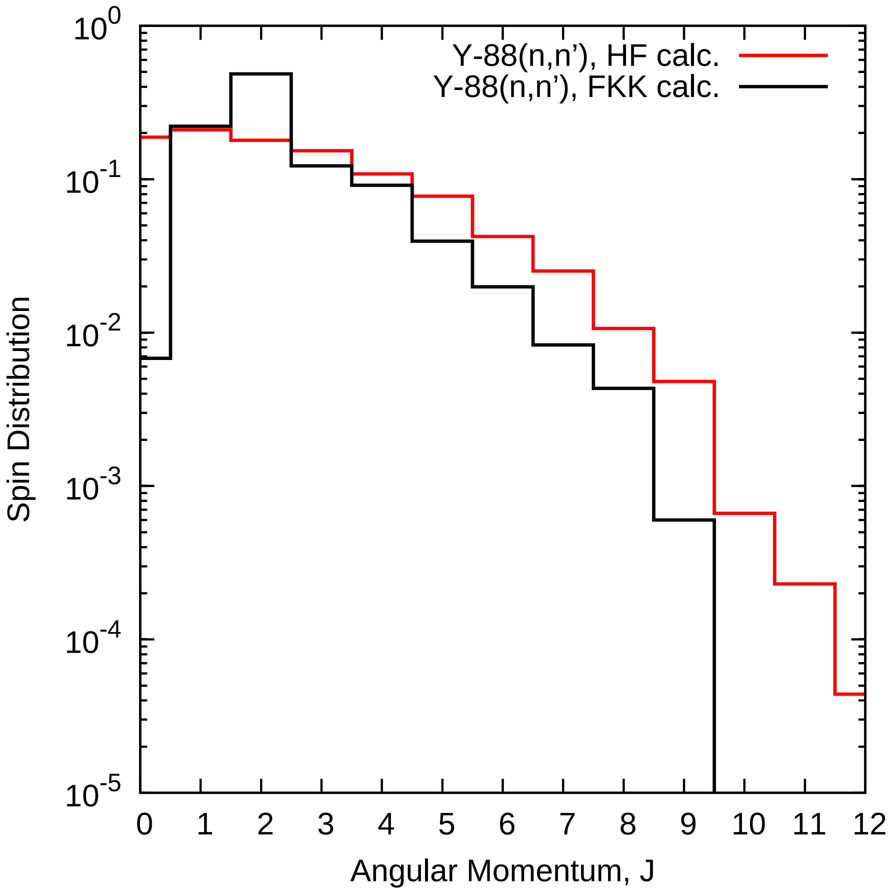



Baba (1990)
MSD
total neutron emission
(a) 30 deg
(b) 60 deg
(c) 90 deg
(d) 120 deg
(e) 150 deg
d²σ/dEdΩ [mb/MeV sr]
Secondary Neutron Energy [MeV]
1
10
100
1000
0
2
4
6
8
10
12
14
16

Pre-Compound Spin Distribution

Spin Distribution of Residual Nucleus

- ^{87}Y$+n$ reaction at E_n =14 MeV.
- Excitation energy of 6 MeV
- Koning-Delaroche global optical potential for incident neutron.
- Ground state spin $I = 1/2^-$ is assumed to be zero.
- FKK calculation does not have a high J component, because of p-h configurations.

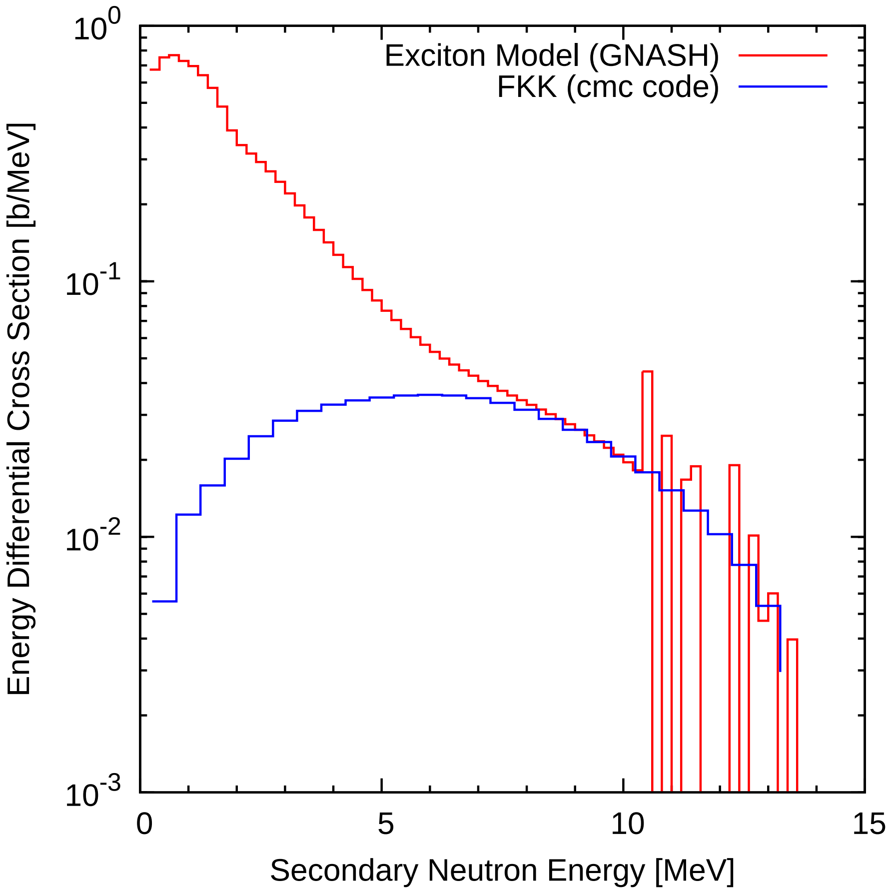


Los Alamos

Energy Spectrum

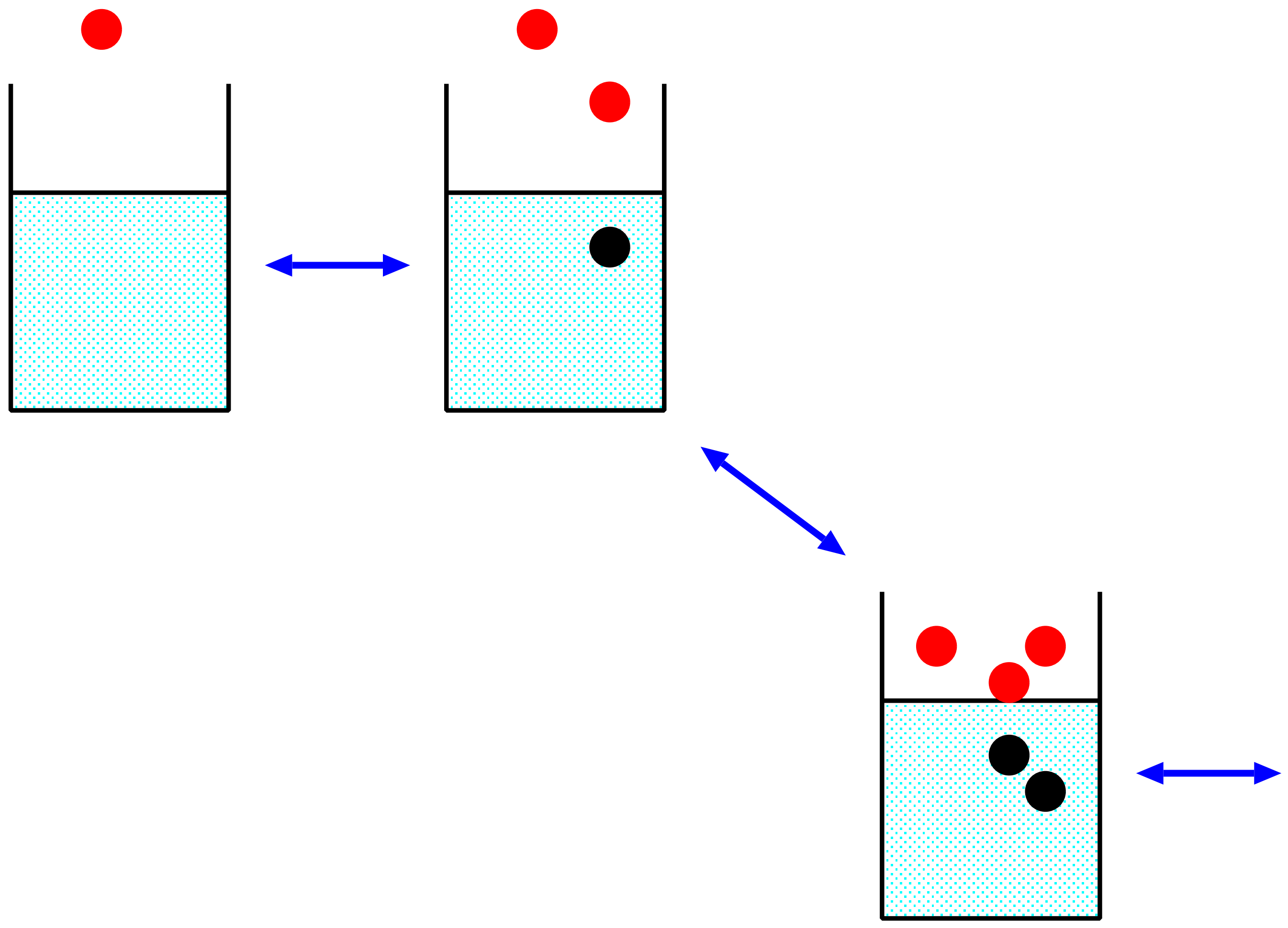
Cmparison of FKK calc. with Exciton Model

- 14 MeV neutron induced, neutron emission reaction on ^{87}Y.
- The FKK MSD calculation is re-normalized to GNASH calculation (Exciton model).
- The MSD cross section is 20% of total reaction cross section.



Los Alamos

Dominant Process at 14 MeV



Concluding Remarks

- Spin-distribution of the pre-equilibrium process can be calculated with quantum mechanical theories — FKK, NWY, and TUL.
- Microscopic calculations of both MSC and MSD were described.
- MSC contribution is very small.
- For ^{87}Y(n, n') reaction at 14 MeV, MSD is about 20% of total reaction cross section, and the compound reaction is still a dominant process at low energies.
- Spin-distribution of the residual nucleus may not have a big impact on the surrogate reaction technique if an incident neutron energy is not so high, however, further study is needed (quantitatively):
  - Probabilities of γ-ray cascade
  - High energy reactions
  - Large target spin

Los Alamos